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ADAPTIVE CONTROL OF SOUND RADIATION FROM A PLATE INTO AN ACOUSTIC CAVITY USING ACTIVE PIEZOELECTRIC-DAMPING COMPOSITES

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ABSTRACT

Sound radiation from a flexible, flat plate into a three-dimensional cavity is controlled using patches of Active Piezoelectric-Damping Composites (APDC). The plate which is a 29.8 cm x 29.8 cm x 0.04 cm, is made of aluminum. It is mounted to form one of the boundaries of a 29.8 cm x 29.8 cm x 75 cm enclosure with five rigid walls made of acrylic. An APDC treatment of dimensions 5cm x 5cm x 0.03125cm is located at the center of the panel on the inner side facing the enclosure. The APDC treatment consists of 25% lead zirconate titanate (PZT-5H) fibers embedded across the thickness in a viscoelastic, polymeric resin matrix. Silver-epoxy electrodes are provided for electrical connections. The presence of the piezoelectric fibers allows one to control the compressional damping characteristics of the composite material. The panel is excited by tonal disturbances and a digital, adaptive Least Mean Square (LMS) controller

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13. ABSTRACT (Maximum 200 words) Instrumentation is needed to subject a wide variety of flexible systems to controlled vibrations in order to evaluate their performance when provided with appropriate passive and active vibration and noise control systems. The evaluation process will involve monitoring the vibration and noise radiation of these systems using a scanning laser vibrometer system to be acquired through this DURIP program. With such capabilities, it would also be possible to identify the sources contributing to excessive vibration and recommend the structural modifications necessary to meet the stringent constraints imposed on the operation of these systems. The proposed instrumentation will provide a general purpose facility for on-ground testing of critical systems such as the Viewing Imager/Gimballed Instrumentation Laboratory (VIGIL) of the Ballistic Missile Defense Organization (BMDO). Such thorough on-ground testing is essential to ensuring satisfactory performance of these critical systems when deployed in space for autonomous operation.					
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is used to study the effectiveness of the APDC treatment. For the considered panel-enclosure system, high attenuations in the sound pressure level are realized when the disturbance frequency is close to the fundamental frequency of the system. Attenuations in the panel vibration level are also obtained. A scanning laser vibrometer is used to measure the panel surface velocity field in the uncontrolled and controlled cases. The results obtained in this experimental study demonstrate the potential for using the APDC treatments in active structural acoustics control which is important in controlling the interior noise in aircraft cabins and automobiles.

1. INTRODUCTION

Passive damping treatments have been successfully used, for many years, to damp out the vibration of a wide variety of structures ranging from simple beams to complex space structures (Nashif et al. 1985). However, the effectiveness of these treatments has been limited to a narrow operating range because of the significant variation of the damping material properties with temperature and frequency. It is, therefore, difficult to achieve optimum performance by using only passive treatments. Hence, treatments which are a hybrid combination of active damping and passive damping treatments have been proposed as a viable alternative to the conventional passive damping treatments. Such hybrid treatments aim at using various active control mechanisms to augment the passive damping in a way that compensates for its performance degradation with temperature and/or frequency. Among the commonly used hybrid treatments are the ElectroMechanical Surface Damping (EMSD) treatments (Ghoneim 1995, Hagood and

von Flotow 1991), the Active Constrained Layer Damping (ACLD) treatments (Balachandran et al. 1997, Baz et al. 1996, Poh et al. 1996, Veeramani and Wereley 1996, Huang et al. 1995, Liao and Wang 1995, Shen 1995) and the Active Piezoelectric-Damping Composites (APDC) (Reader and Sauter 1991, Gentilman et al. 1994, Ghandi . and Hagood 1996, DeGiorgi and McDermott 1997). In the EMSD treatments, a piezo-electric film is used to passively constrain the deformation of a visco-elastic layer which is bonded to a vibrating structure. The film is used also as a part of a shunting circuit that is actively tuned to improve the damping characteristics of the treatment over a wide operating range. A similar configuration is employed in the ACLD treatments. However, the piezo-film is actively strained in such a manner to enhance the shear deformation of the visco-elastic damping layer in response to the vibration of the base structure. In the APDC treatments, an array of piezo-ceramic rods embedded across the thickness of a visco-elastic polymeric matrix are electrically activated to control the compressional damping characteristics of the matrix that is directly bonded to the vibrating structure.

Therefore, in the three hybrid damping treatments described, one can identify three distinct damping augmentation mechanisms. In the EMSD, the augmentation results from the energy dissipation in the shunted electric circuitry whereas in the ACLD and the APDC treatments, the augmentation is attributed to the enhanced shear and compressional deformations of the visco-elastic layers, respectively.

As the EMSD and the ACLD treatments have been extensively studied, our prime emphasis in the present study is placed on demonstrating the potential and the effectiveness of the APDC treatments in controlling the structural vibrations and

associated sound radiation into acoustic cavities. With such an emphasis, the application range of the APDC can be extended beyond its current use as an acoustic transducer (Wang et al. 1995).

This paper is organized as follows: In Section 2, the concept of the Active Piezoelectric Damping Composite (APDC) is presented. In Section 3, the LMS algorithm is briefly described. The effectiveness of the APDC treatment in damping the vibration and sound radiation from the plate into the cavity is illustrated in Section 4. A brief set of remarks are given in Section 5.

2. ACTIVE PIEZO-ELECTRIC DAMPING COMPOSITE (APDC)

Active Piezo-electric Damping Composites (APDC) have been gaining wide acceptance because of their superior electromechanical coupling and low mechanical impedance characteristics (Reader and Sauter 1993 and Smith and Auld 1991). The most commonly used APDC type is the "1-3" composite that has been developed primarily for use as an acoustic transducer (Gentilman et al. 1994, Wang et al. 1995). In that composite, piezo-ceramic rods (PZT-5H) are embedded across the thickness of a polymer matrix as shown in Figure (1). The PZT rods are polarized along their length and extend in "one dimension" between two electrodes deposited on the top and bottom surfaces of the polymer matrix. The matrix itself extends spatially in all the "three dimensions" to give the composite its "1-3" designation (Newnham et al. 1978).

It is important to note that the APDC has several advantages over plain Lead Zirconium Titanate (PZT) patches. These advantages include improved hydrostatic

piezoelectric charge coefficient than increases its effectiveness as an underwater transducer. Also, the flexibility of the polymer matrix enables the APDC to be bonded to complex structural shapes and makes it capable of absorbing considerable impact energies as compared to the brittle plain PZT patches. Furthermore, the APDC with its built-in damping provides active control characteristics which are inherently stable. Such features of the APDC, when coupled with its low mass density, are particularly important in manufacturing light weight smart structures.

Typically, the APDC has used at very high frequencies in the order of MHz. However, in the present study, the APDC is used to control vibration and sound radiation at frequencies lower than 100 Hz. Such low frequency components are present in the vibration and noise fields of large flexible structures, such as satellites, aerospace structures and helicopters.

3. THE ADAPTIVE LMS ALGORITHM

The LMS algorithm is a gradient-based algorithm, which is commonly used in adaptive signal processing (Widrow and Stearns 1985) and active noise control (for example, Clark and Fuller 1993). In this algorithm, a reference signal $x(k)$ is adaptively filtered, as shown in Figure (2) to generate the necessary control action. In the present study, the reference signal is taken as the periodic signal exciting the plate. The filtering process utilizes an adaptive Finite Impulse Response (FIR) filter whose i^{th} coefficient, at the k^{th} time sample, is $w_i(k)$. The filter output $y_1(k)$ is then given by

$$y_1(k) = \sum_{i=1}^N w_i(k) x(k-i) \quad (1)$$

where N is the number of stages of the filter. Considering the plate/enclosure dynamics, one obtains an error signal $e(k)$ which is given by

$$e(k) = d(k) + C(z) y_1(k) \quad (2)$$

where $d(k)$ is the disturbance and $C(z)$ is the transfer function of the plate/enclosure system. The transfer function C is assumed to be linear, time-invariant, discrete and described in the following form:

$$C(z) = \sum_{j=1}^n C_j z^{-j} \quad (3)$$

where z is a complex number and z^{-1} is the unit delay operator.

In the present study, the error signal is determined by measuring the sound pressure signal at critical locations inside the enclosure and utilizing the adaptive learning capabilities of the LMS method to update the weights $w_i(k)$ in order to minimize the square of the error signal. Such a minimization process results in updated weights $w_i(k+1)$ that are given by

$$w_i(k+1) = w_i(k) - 2 \mu e(k) R(k-i) \quad (4)$$

where μ is a positive constant that defines the learning rate and the convergence speed of the adaptation process and $R(k-i)$ is a "Filtered-X" signal given by

$$R(k-i) = \sum_{j=1}^n C_j x(k-i-j) \quad (5)$$

From equation (4), it can be seen that after the weights are adapted according to the LMS algorithm to drive the error $e(k)$ to zero, no further adjustments to the filter weights will occur.

The convergence of LMS algorithm depends upon the appropriate choice of the learning rate or the convergence coefficient μ . Starting with arbitrary initial weights, the algorithm will converge and remain stable as long as the parameter μ is greater than zero but less than the reciprocal of the largest eigenvalue λ_{\max} of the input auto correlation matrix $E[x(k) x(k)]$ (Widrow and Stearns 1985); that is,

$$1/\lambda_{\max} > \mu > 0 \quad (6)$$

Within these bounds, convergence is guaranteed and the filter weights will converge to their optimum value, where an extremum of the error function is realized.

4. EXPERIMENTS WITH THE PLATE/APDC/CAVITY SYSTEM

4.1. Introduction

The effectiveness of the APDC in controlling the vibration and sound radiation from a plate into an acoustic cavity is demonstrated experimentally by using the LMS algorithm described in Section 3. This section is organized into four subsections with the main experimental results presented in subsection 4.4.

4.2. System Properties

A thin squared aluminum plate of dimensions 0.4 mm x 0.298 m x 0.298 m is used in this study. The plate is mounted, with all of its edges clamped, to form a flexible side of an acoustic cavity that has the dimensions of 0.298 m x 0.298 m x 0.75 m. The remaining five sides of the cavity are made of thick acrylic sheets which are 1.25 cm thick. The plate is treated with a single APDC patch bonded to the plate center. In Figure (3) a photograph of the plate/cavity/APDC patch system is shown. The APDC patch, used in this study, has the dimensions 0.05 m x 0.05 m x 0.003125 m. It is made of a polyurethane damping material with ceramic piezo-electric fibers embedded across its thickness. The volume fraction of the piezo-electric fibers is 25% . Detailed properties of the fibers, the matrix and the equivalent active layer of the APDC patch are given in the work of Shields (1997).

In Table (1), the fundamental frequency and associated damping factor of the plate and the plate/Cavity system are given for cases with and without the APDC treatment. These properties were using classical modal analysis techniques (Ewins 1984).

Table (1) - Modal properties of the plate/cavity/patch system

Property	Uncoupled Plain Plate	Uncoupled Plate/APDC	Coupled Plain Plate	Coupled Plate/APDC
Freq. - Hz	37	27.5	53.5	34.5
Loss factor	.04	0.032	0.038	0.04

4.3. Experimental Set-Up

In Figure (4), a schematic drawing of the experimental set-up used for testing the plate/cavity/APDC system is shown. The plate vibration, at a specific location, is monitored by using a laser sensor (Model IIIB-LA40HR, Aeromat Corp., New Providence, NJ). The selected location is 0.2m and 0.1m off the plate center in order to observe all the plate vibration modes. The spatial distribution of the plate surface velocity is monitored by a scanning laser vibrometer (Ometron, VPI 4000, Sterling, VA). The sound pressure inside the cavity is measured by using a microphone (Model 4165, Bruel & Kjaer, Denmark) placed at a distance of 0.23 m from the plate center. The microphone signal is amplified by using a Bruel & Kjaer amplifier (Model 5935).

The plate is excited acoustically by using an electromagnetic speaker placed, outside the cavity, at a distance of 5 cm from the center of the plate. The signal driving the speaker is used as the reference input signal for the LMS controller. The laser sensor and the microphone output signals are used, in separate experiments, as the error signals for the LMS controller.

4.4. Performance of the Plate/APDC/Cavity System

The sound pressure level inside the enclosure, the vibration amplitude of the aluminum plate as well as the control voltage sent to the piezo-films are monitored by acquiring the microphones and laser sensor signals using a dual channel FFT analyzer. The effect of the learning rate coefficient μ on the performance characteristics of the APDC treatment in attenuating the sound inside the enclosure is also investigated. In the

present study, number of stages N used in the FIR filter are 14 and the identified transfer function $C(z)$ of the plate/cavity/APDC is of order 7 with two time delays. The coefficients of the transfer function are obtained by using the MATLAB Identification Toolbox (The MATH WORKS, Inc., Natick, MA 1997).

4.4.1. Plate vibration as error signal

The performance of the APDC is examined first when the plate vibration, at the laser sensor location, is used as the error signal for the LMS controller. In Figure (5-a), the corresponding time response of the plate vibration is shown when the uncontrolled-coupled system is excited at its first mode frequency of 34.5 Hz. The effect of activating the APDC treatment on the plate response is shown in Figure (5-b). The APDC treatment results in almost 95% attenuation of the error signal. Figure (5-c) shows the required control voltage necessary to produce the displayed attenuation. The time required for the adaptive controller to converge is approximately 3.5 seconds as can be seen in Figure (5-b). The frequency spectra of the steady-state laser sensor error signals for the uncontrolled and the controlled cases are shown in Figure (6-a). The corresponding spectrum for the control voltage input is shown in Figure (6-b). From Figure (6-b), it is seen that the peak control voltage use for the APDC treatment is about 240 volts.

The time histories of the sound pressure level for the uncontrolled and controlled aluminum plate are shown in Figures (7-a) and (7-b), respectively. The corresponding characteristics in the frequency domain are shown in Figure (7-c). From Figures (6) and

(7), one can discern that activating the controller has damped out the plate vibration which in turn has resulted in attenuating the sound pressure level. Therefore, the attenuation of the radiated sound from the aluminum plate is attained through the "modal suppression" phenomenon as described by Pan and Hansen (1991). However, in other cases, this may not generally be true (e.g., Sampath and Balachandran, 1997).

The effect of changing the adaptive learning rate μ on the performance of the Filtered-X LMS controller can be seen from the time history plots of the filter weights shown in Figure (8). It is to be noted that all the results reported for the system with the APDC treatment are obtained with $\mu=10\text{E-}10$; this value corresponds to a balance between speed and stability of convergence. Also, all the frequency spectra are measured after convergence has been achieved.

4.4.2. Sound pressure as error signal

In the following section, the performance of the APDC is examined when the microphone signal is used as the error signal for the LMS controller. Figure (9-a) shows the time response of the sound pressure level of uncontrolled system when it is excited at 34.5 Hz. The response of the controlled system and the corresponding control voltage are shown in Figures (9-b) and (9-c) respectively. The displayed response, the resulting attenuation and the control effort are qualitatively similar to those shown in Figure (5) when the plate vibration is utilized as the error signal. The corresponding frequency spectra of the error microphone signal and the control voltage are shown in Figures (10-a)

and (10-b). A peak control voltage of about 240 volts is used to activate the APDC treatment.

The effect of using the sound pressure level as the error signal on the time history of the plate vibration is shown in Figure (11) both in the time and frequency domains. It is evident that the LMS controller has been equally effective in attenuating both the sound radiation into the cavity and the plate vibration. The results displayed are obtained with a learning rate of $5E-11$.

The effect of changing the adaptive learning rate μ on the performance of the Filtered-X LMS controller is shown in the time history plots of Figure (12).

4.4.3. plate surface velocity distribution

The effectiveness of the APDC treatment in controlling spatially the structural vibration of the test plate is examined by using a scanning laser vibrometer (VPI 4000, Ometron, Sterling, VA). In Figure (13), a picture of the plate/APDC assembly is shown along with a qualitative display of the spatial distributions of the plate surface velocity of the uncontrolled and controlled cases. The effectiveness of the APDC in attenuating the plate surface velocity in the transverse direction is evident. In Figure (14), a quantitative display of the iso-surface velocity contours is shown for the uncontrolled and controlled cases. For the uncontrolled case, a maximum surface velocity of 1.5 mm/s (rms) is observed. This value reduces to a value of 0.3 mm/s (rms) when the LMS controller converges to its steady-state conditions.

5. CONCLUSIONS

In this paper, an experimental demonstration of the effectiveness of Active Piezoelectric-Damping Composites (APDC) in controlling the vibration and sound radiation from flexible plates into acoustic cavities has been provided. The active control scheme was realized by using a digital, adaptive filtered-X LMS algorithm implemented with different error signals. Tonal disturbances with a frequency close to the fundamental frequency of the plate/cavity system were considered and attenuation of related sound pressure levels inside the enclosure and plate vibration were demonstrated. In the present study, the APDC treatment was used primarily to control the flexural vibrations of the plate. This study demonstrates that the APDC treatment can be used in various applications to actively control low frequency structural vibration and associated sound radiation. In this manner, the use of the APDC treatments can be extended beyond their conventional use as a high frequency acoustic transducer.

Simultaneous control of multi-modes of vibration of the plate/cavity system with optimally placed sets of APDC patches and acoustic sensors is a natural extension of the present study. Currently, modifications of the APDC patches to include constraining face plates is now under investigation experimentally and theoretically. Comparisons between the performance of the APDC with that of the ACLD treatments are essential to define the merits and limitations by using quantitative norms such as the loss factor and the input control energy.

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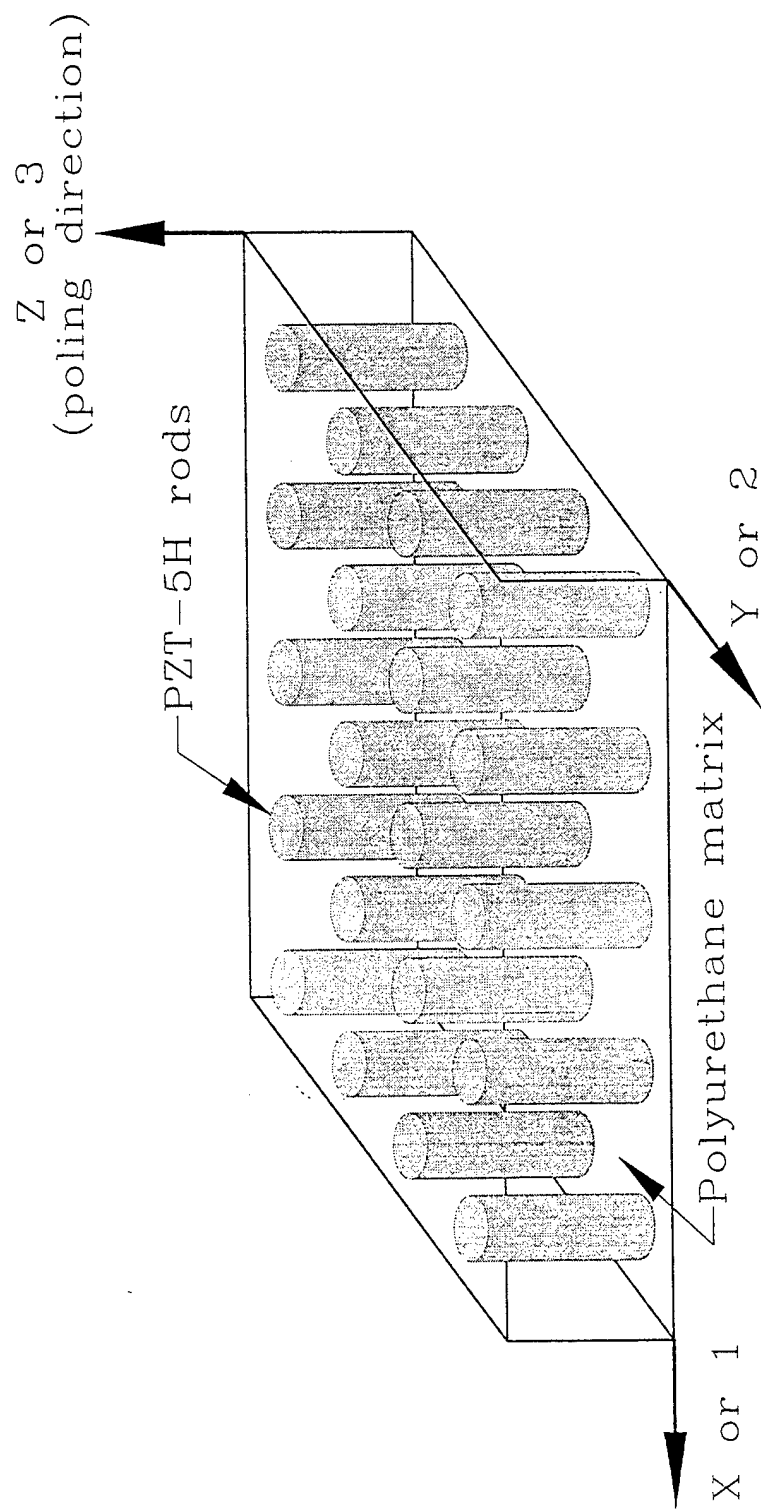


Figure (1) – Schematic drawing of the Active Piezoelectric Damping Composite (APDC)

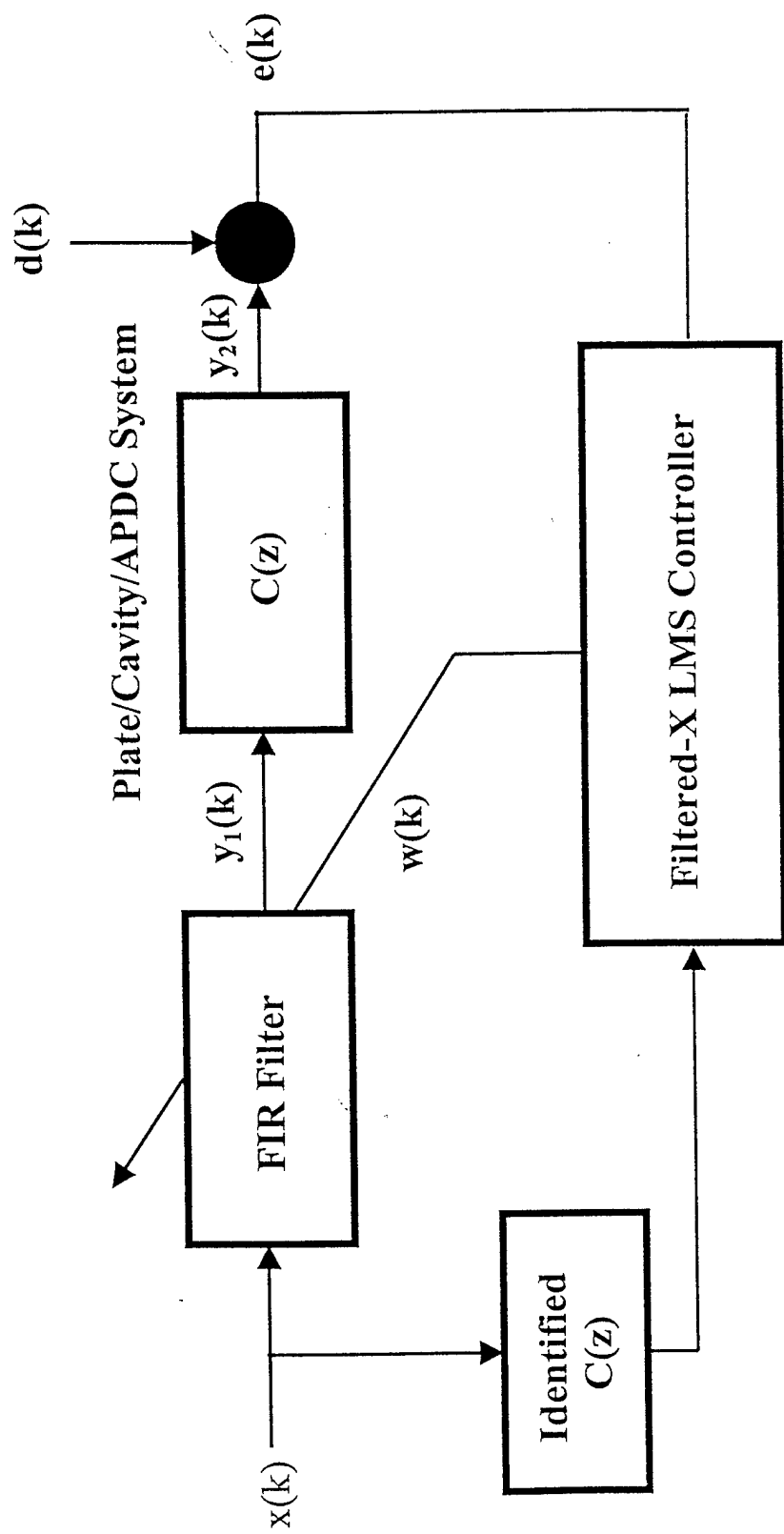
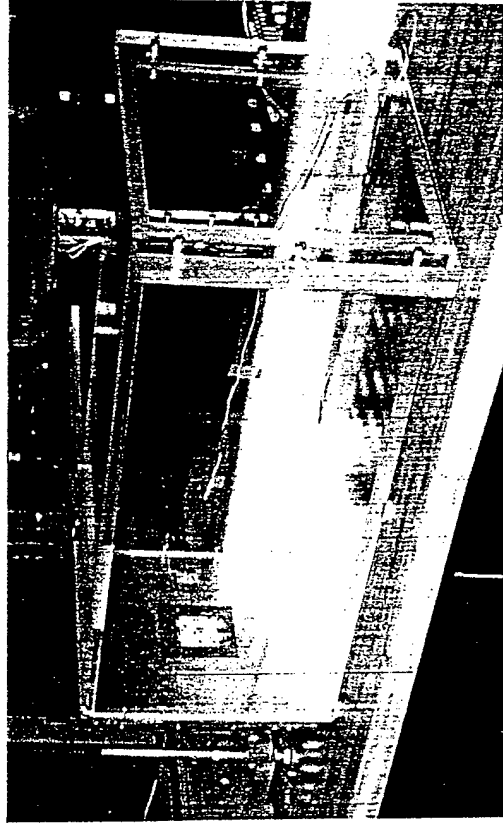


Figure (2) - Filtered-X LMS controller

CAVITY

ALUMINUM PLATE



PIEZO-
PATCH

MICROPHONE

Figure(3) – A photograph of the plate/cavity/APDC system

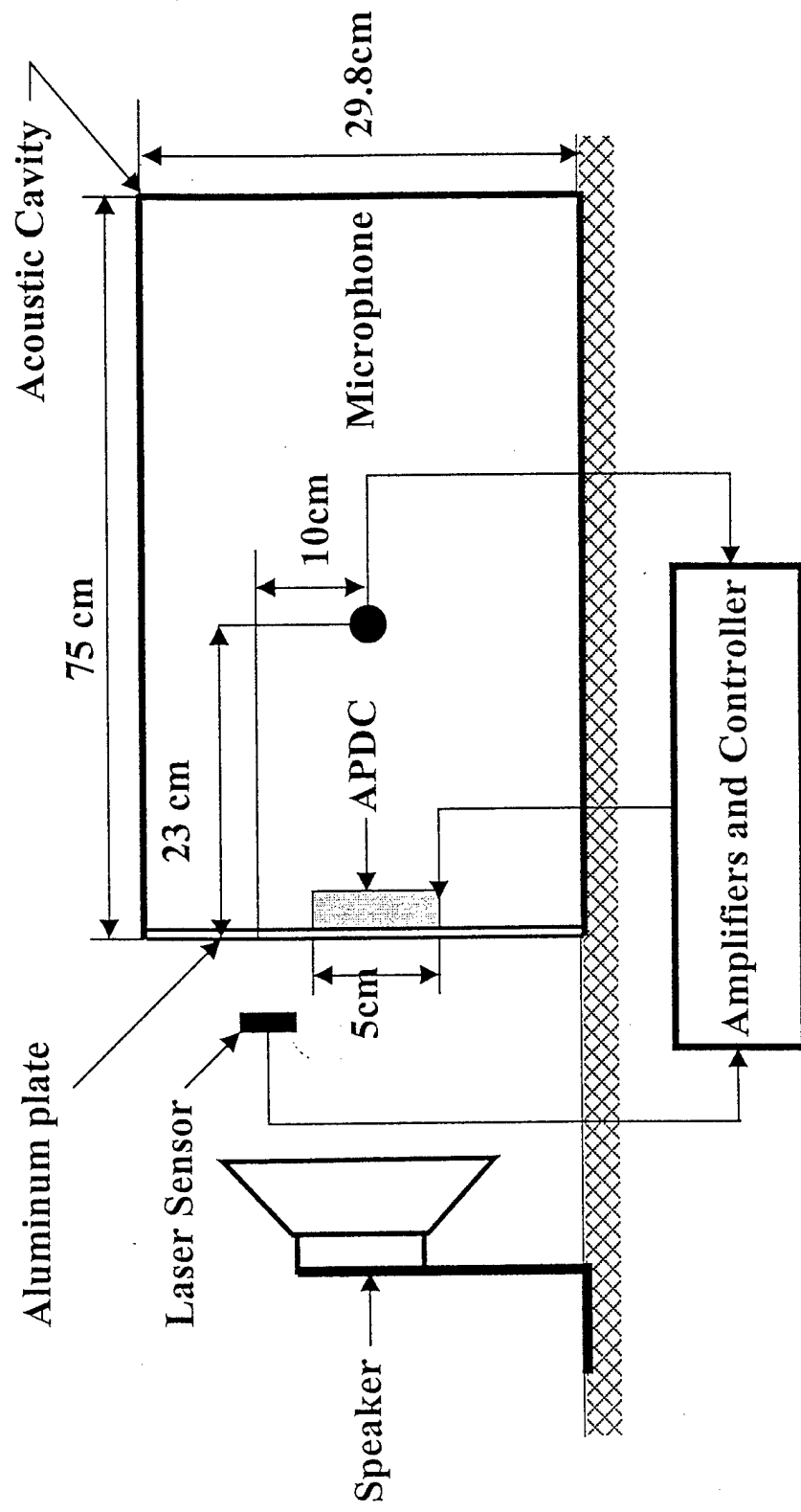


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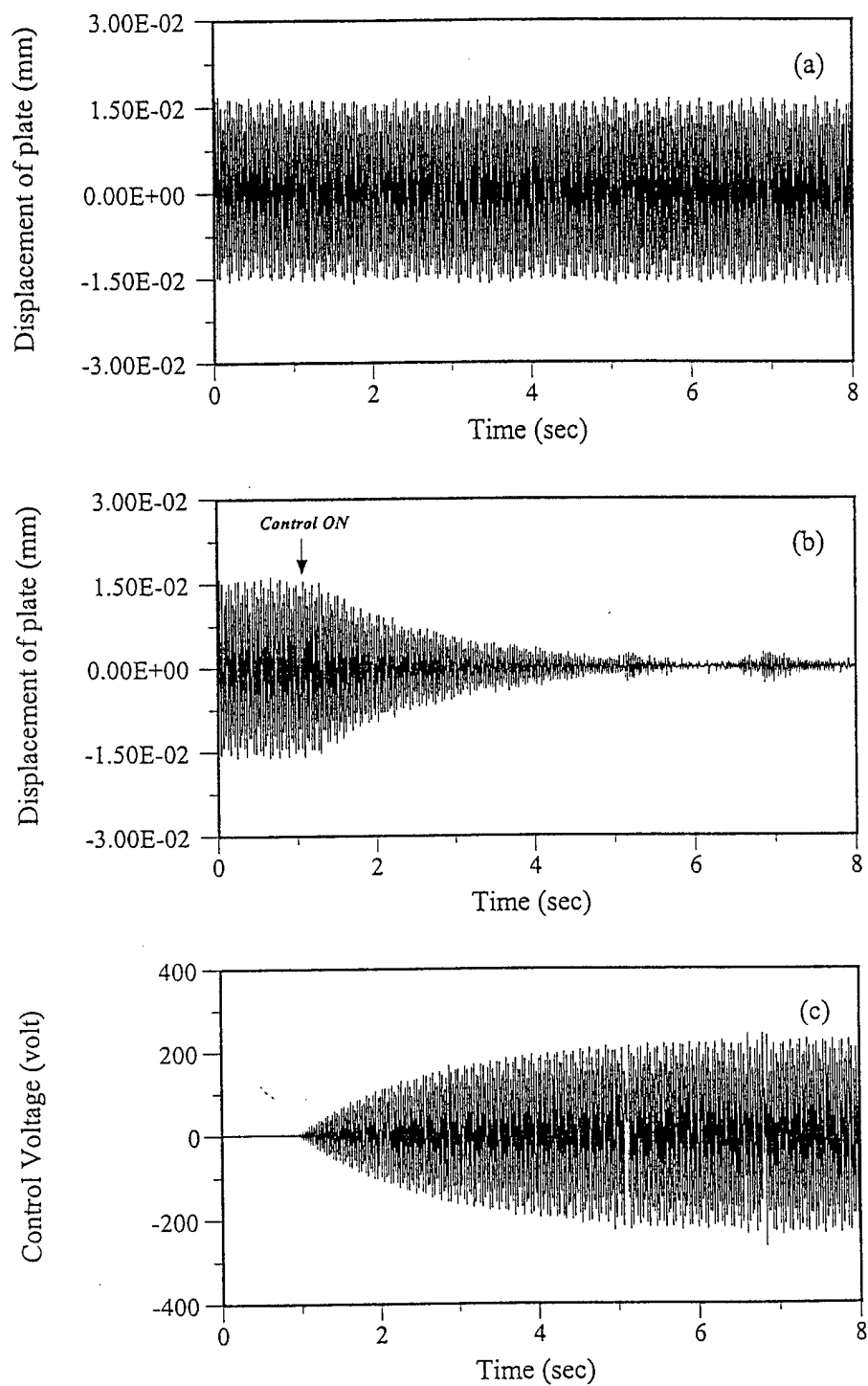


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- b. plate vibration in controlled case
- c. control voltage

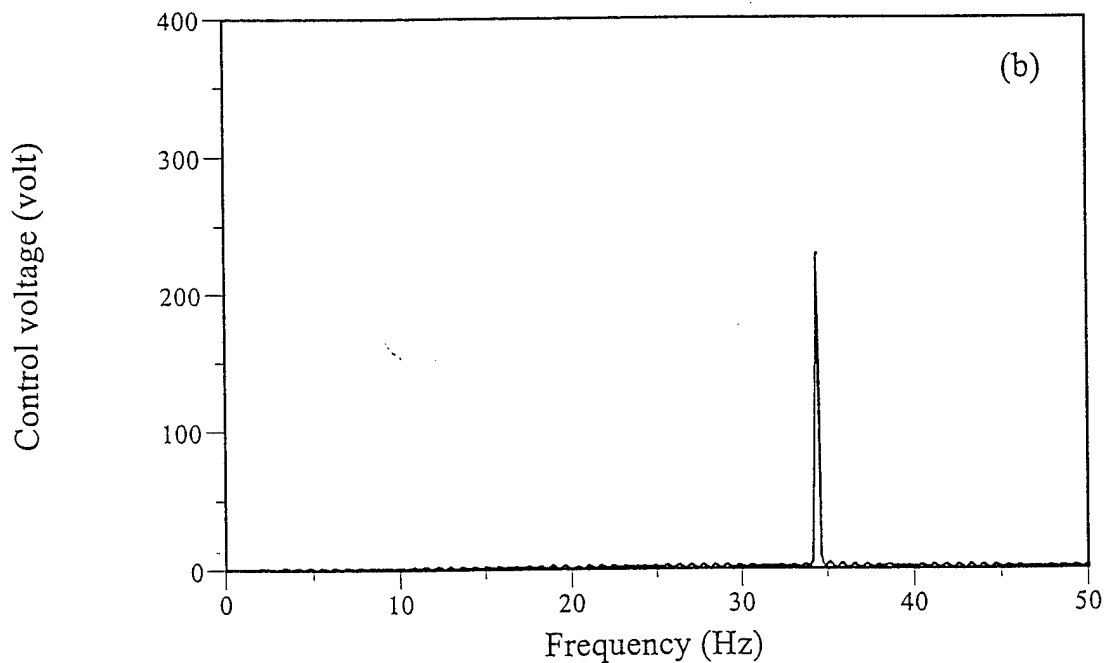
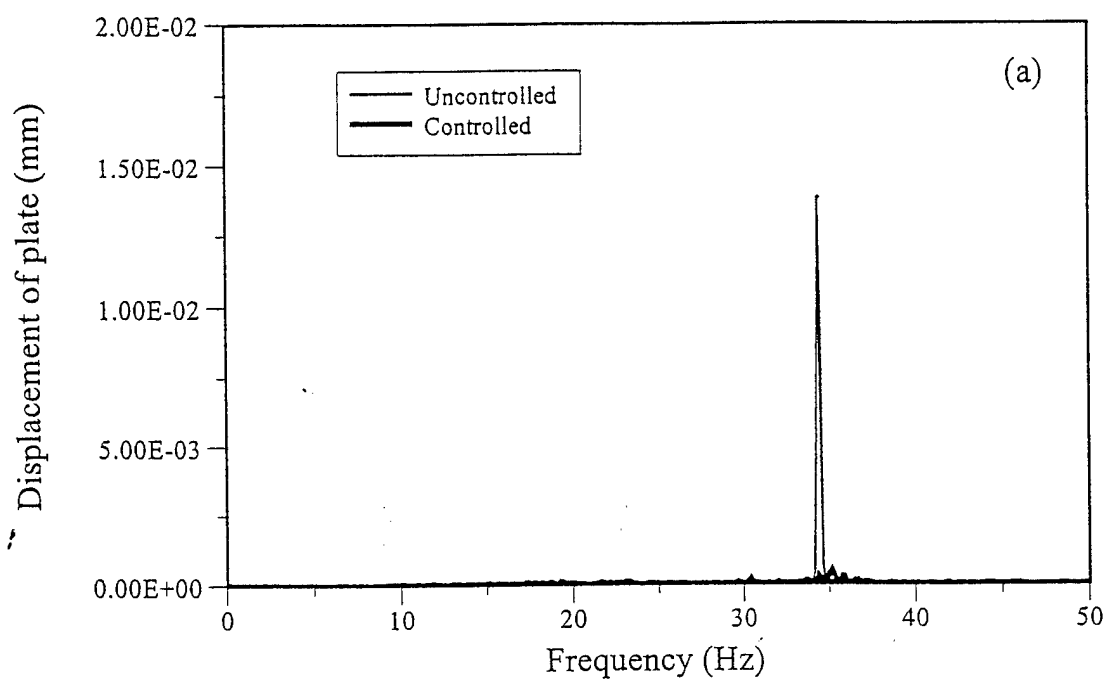


Figure (6) – Frequency spectra of plate vibration and control voltage when using plate vibration as error signal

- a. plate vibration spectra for uncontrolled and controlled cases
- b. control voltage spectrum

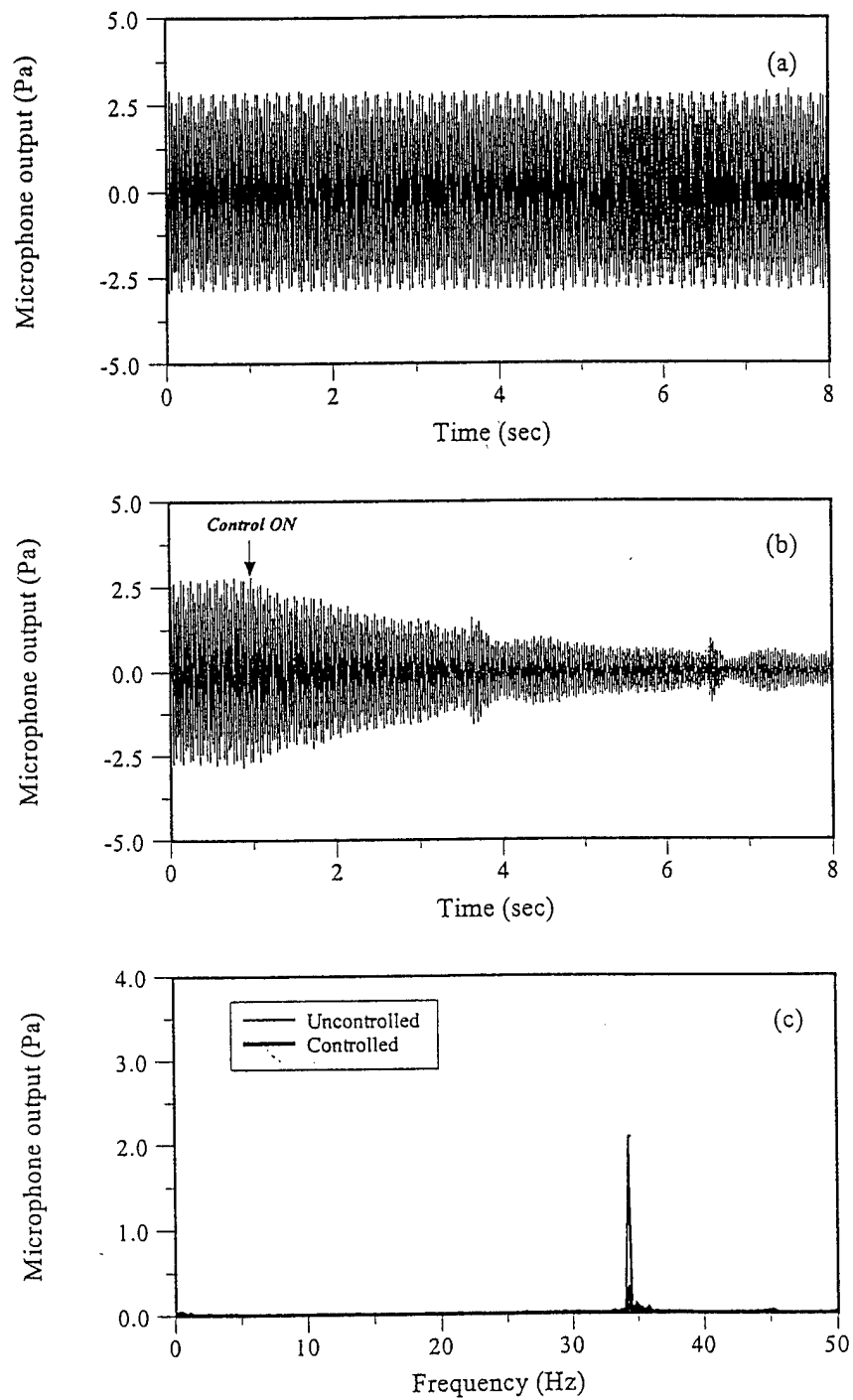


Figure (7) – Sound pressure level when using plate vibration as error signal

- a. time history of uncontrolled case
- b. time history of controlled case
- c. spectra of uncontrolled and controlled cases

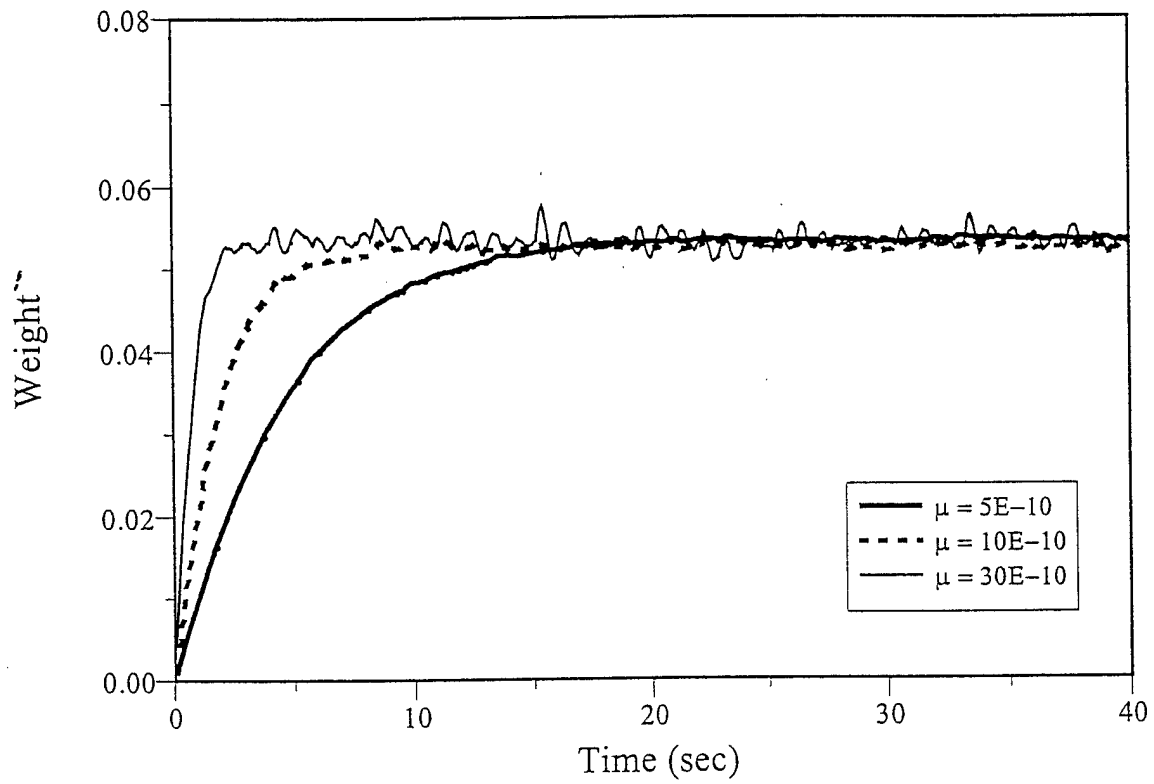


Figure (8) – Effect of learning rate on convergence of filter weights when using plate vibration as the error signal

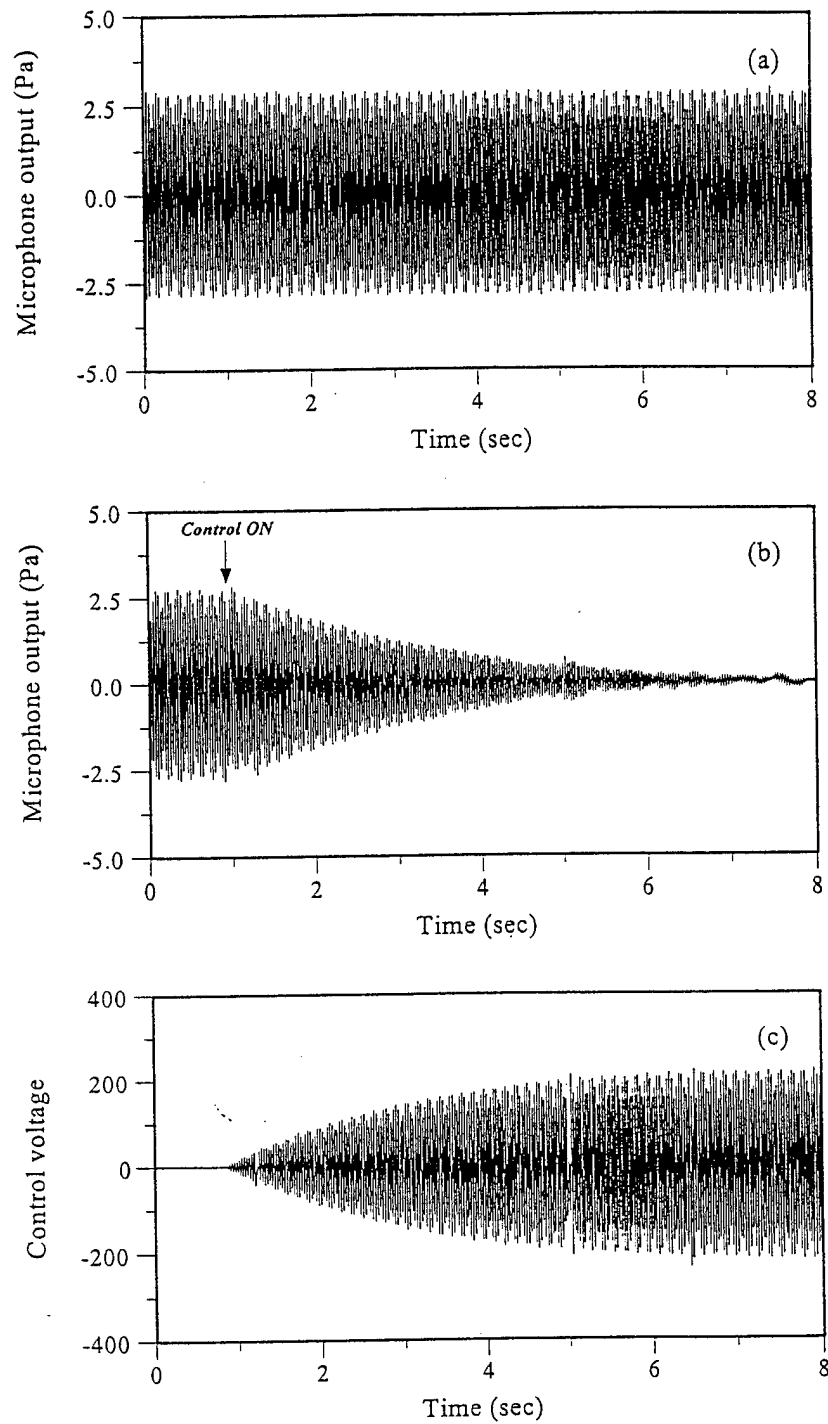


Figure (9) – Time histories of sound pressure level and control voltage when using sound pressure as error signal

- a. sound pressure in uncontrolled case
- b. sound pressure in controlled case
- c. control voltage

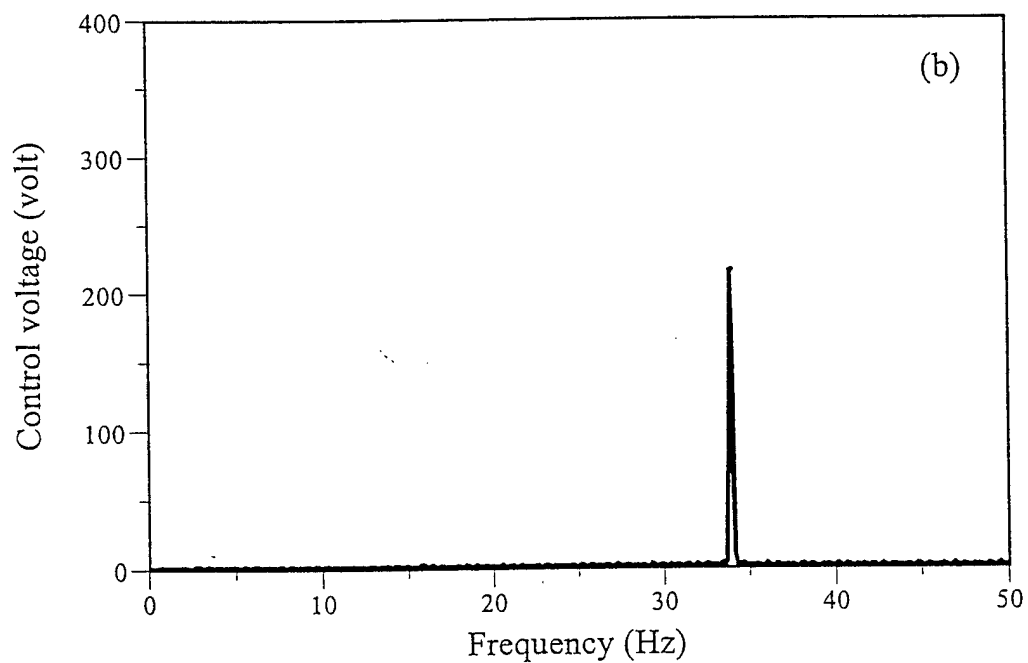
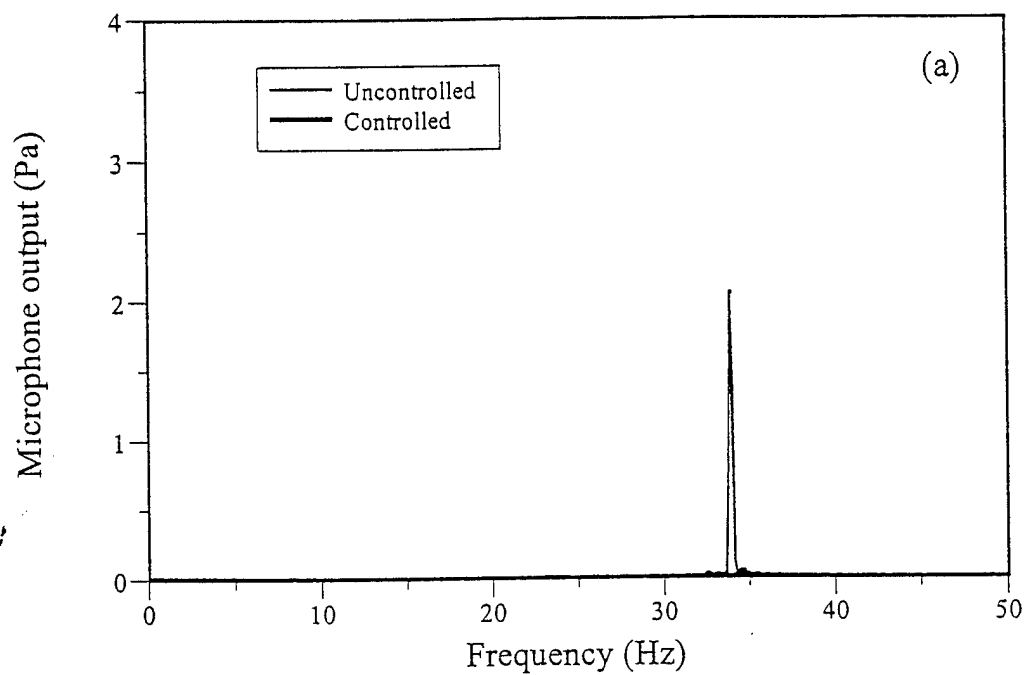


Figure (10) – Frequency spectra of sound pressure and control voltage when using sound pressure as error signal
a. Sound pressure spectra for uncontrolled and controlled cases
b. control voltage spectrum

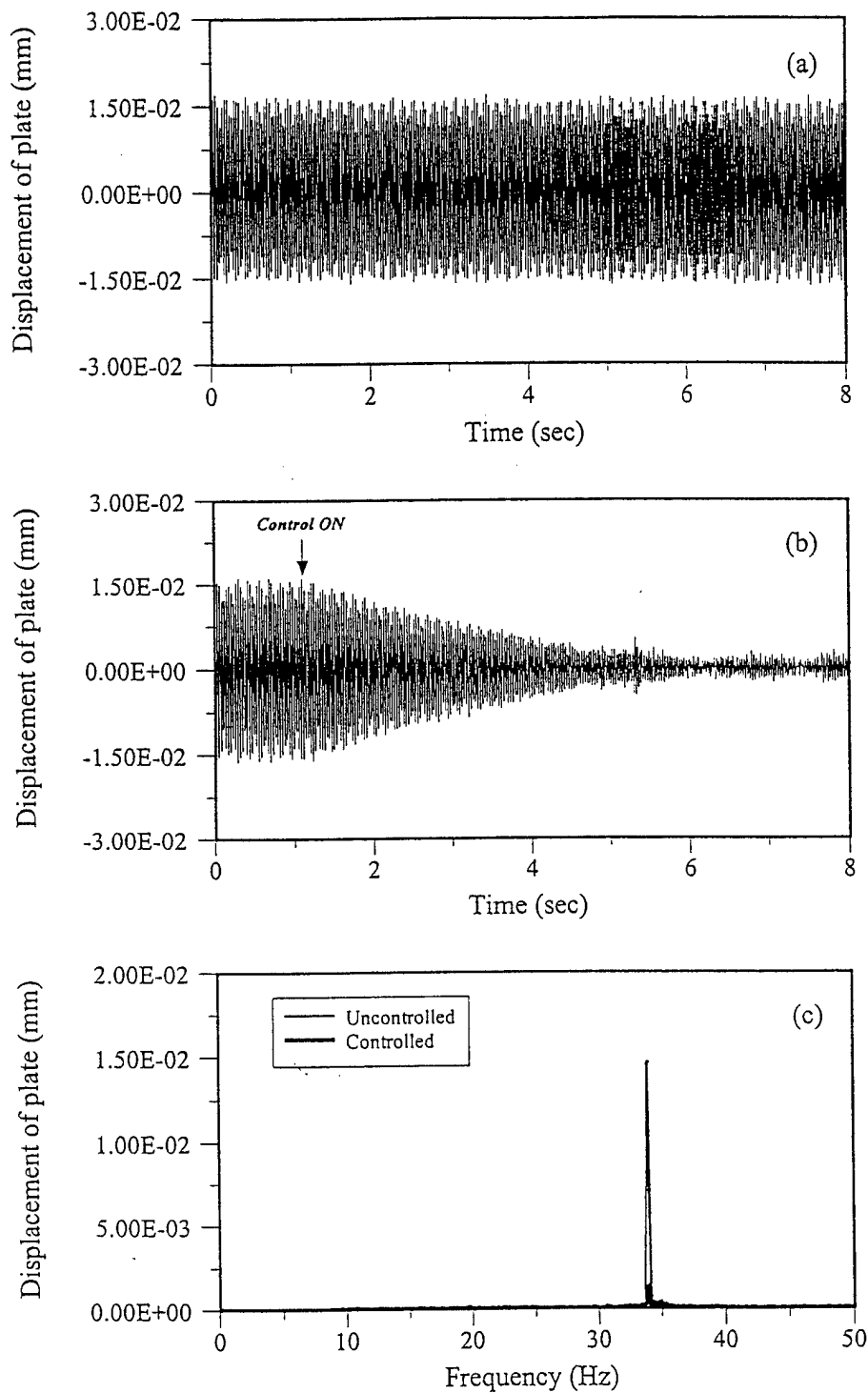


Figure (11) – Plate vibration when using sound pressure as error signal

- a. time history of uncontrolled case
- b. time history of controlled case
- c. spectra of uncontrolled and controlled cases

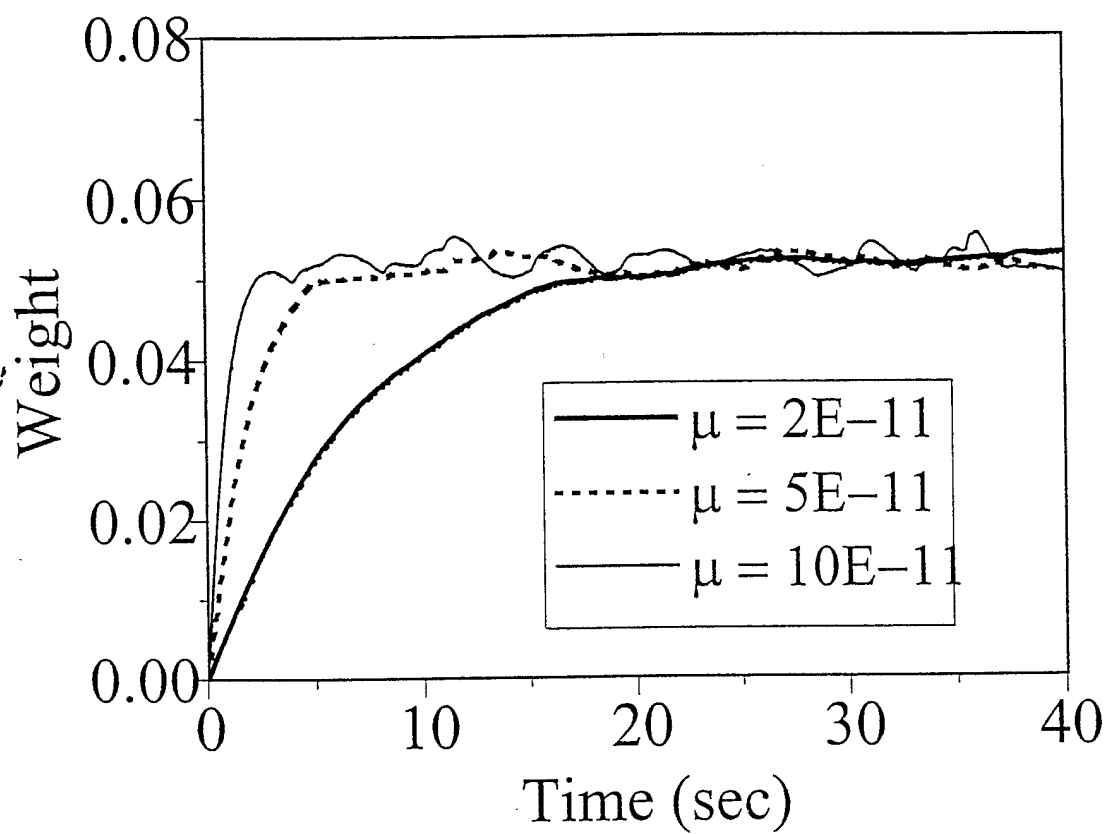
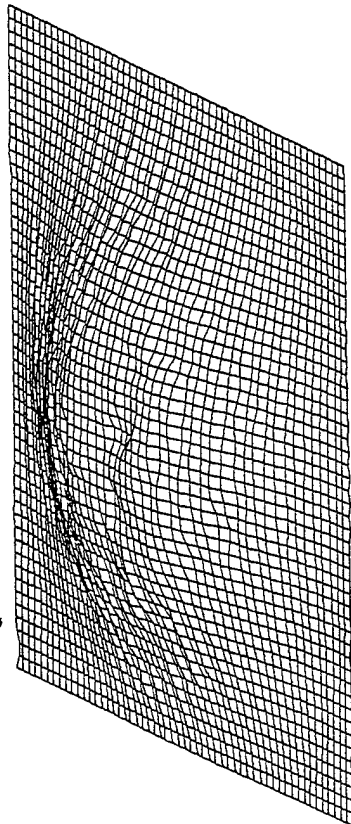
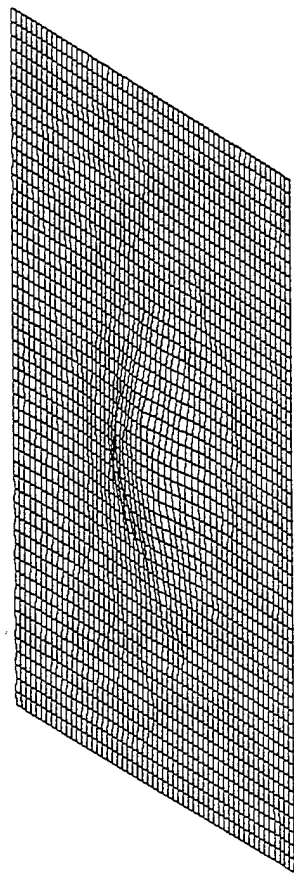


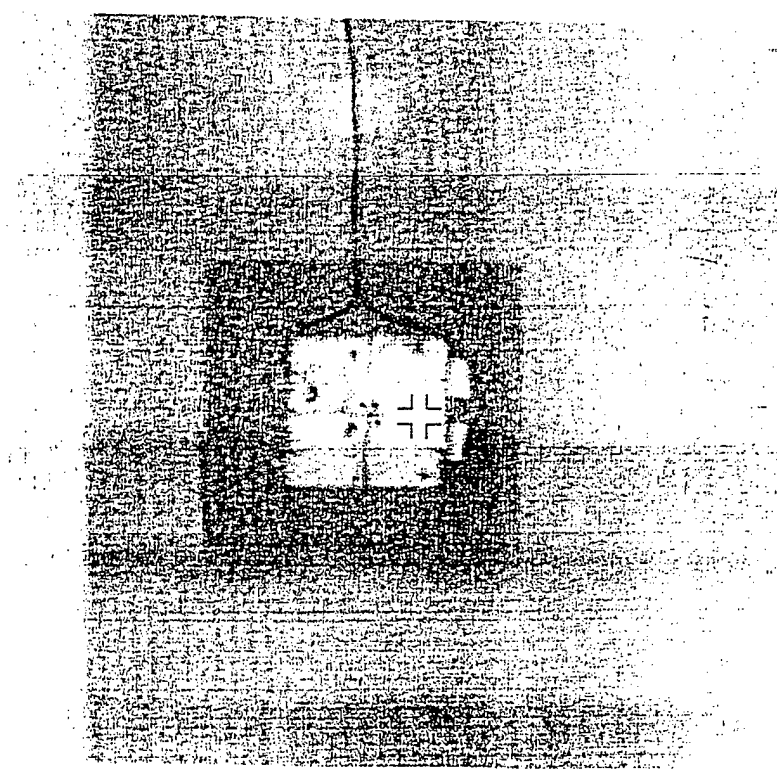
Figure (12) – Effect of learning rate on convergence of filter weights when using sound pressure as the error signal



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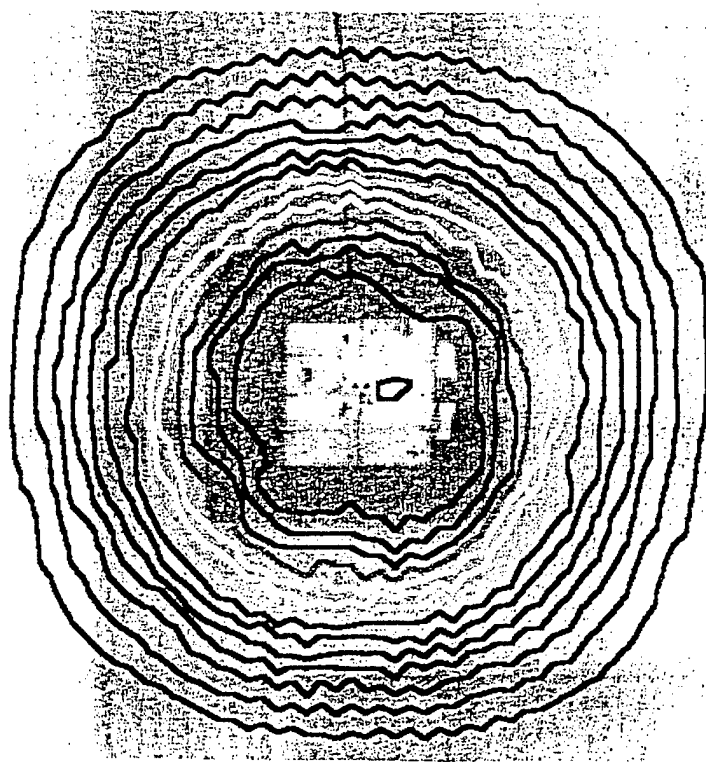
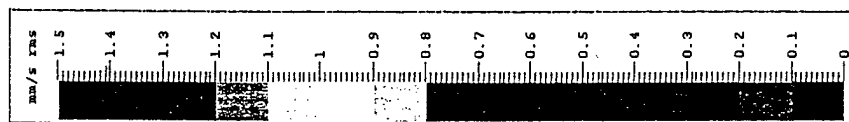


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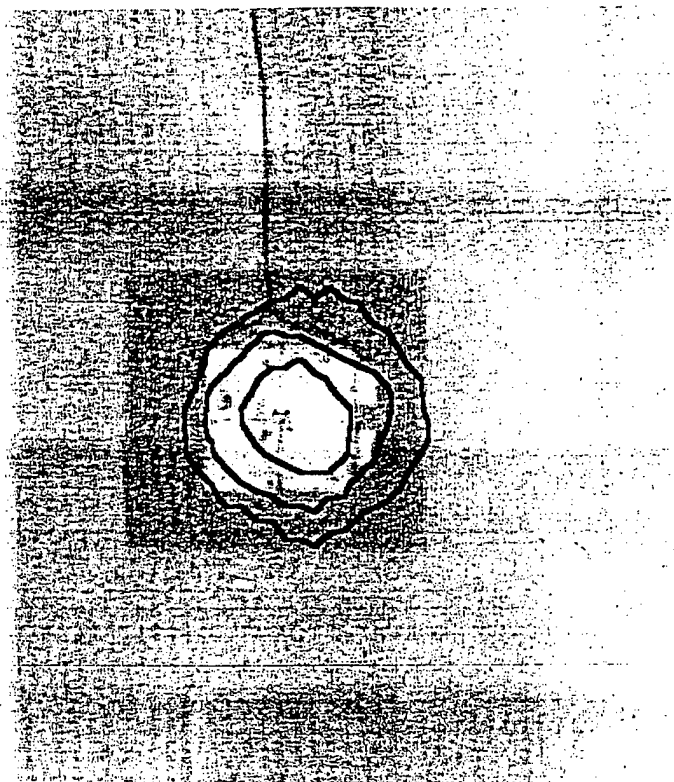


PLATE/APDC

Figure (13) — Qualitative illustrations of surface velocity distribution of the plate in the uncontrolled and controlled cases.



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Figure (14) – Contours of the iso-surface velocity of the plate in the uncontrolled and controlled cases.